Systems and Methods for Measuring Magnetostriction in Magnetoresistive Elements

5   **Field of the Invention**

The present invention relates in general to the measurement
of the magnetostriction constant. More specifically, the
invention relates to such measurements in magnetoresistive
10 devices.

Background of the Invention

There are many situations in which there is a need to
15 measure a magnetic field. Among such situations are the
measurement of position or proximity of a magnetized
portion of a structure, the reactant of stored magnetic
information, the measurement of current flows without the
need of a measuring device in the current flow path, etc.

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Many of the magnetic effects in such situations are
relatively small and therefore require a sensitive magnetic
sensor. A magnetic sensor capable of sensing such small
magnetic field perturbations, and which is economical to
25 fabricate, is provided on the basis of the magnetoresistive
effect. Such magnetoresistive material based magnetic
sensors can be fabricated as thin films when using
monolithic integrated circuit fabrication techniques, and
so can not only be made economically but also made quite
30 small in size. A magnetoresistive material based magnetic
sensor is arranged by providing a magnetoresistive material

to be used as an electrical resistor. A current is passed
therethrough, and the voltage there across will depend on
the effective resistance of the material over the path in
which the current flows. That resistance value will depend
5   in turn on the state of the magnetization of the material.
If the magnetization is parallel to the current flow, what
is the case for Anisotropic Magnetoresistance (AMR), the
material will exhibit a maximum resistance, and it will
exhibit a minimum resistance for magnetization
10   perpendicular to the current flow.

For Giant Magnetoresistance (GMR), the maximum resistance
is for parallel alignment of the magnetization of adjacent
magnetic layers, separated by non-magnetic interface
15   layers. A spin valve system consists of two magnetic
layers, a free layer and a pinned layer. The pinning can be
made by an antiferromagnetic layer or by
antiferromagnetically coupled pinning layers.

20   The current in such systems can be current-in-plane (CIP)
or current-perpendicular-to-plane (CPP). The CPP structure
is normally used in tunneling devices (Tunneling
Magnetoresistance - TMR), where the non-magnetic interface
layer consists of an electrically resistive isolator
25   material.

In the magnetoresistive device there is typically a free
rotating layer with an effective magnetization. An external
field acting on the magnetoresistive material will rotate
30   the magnetization direction therein to change the
resistance of the layer system as a result. The changed

resistance of the material carrying the current causes a voltage drop change across the resistor which can be sensed as an indication of the magnitude of the external field.

5   The effective resistance of such a film will vary as the square of the cosine of the angle between the effective magnetization direction and the current flow direction through the material in the AMR case and as the cosine of the angle of adjacent layers in the GMR or TMR case. The

10   total resistance, however, is usually not of interest but rather the change in resistance in response to a change in the applied external magnetic field. In the AMR case, this change is often best measured at a point along the squared cosine response curve where the curve approximates a linear

15   function.

To provide operation on such a linear portion of the response curve requires that there be an initial angle between the direction of current flow and the nominal

20   direction of magnetization in the absence of any externally applied fields. This can be accomplished in alternative ways in a bias arrangement. The magnetoresistive material can be placed on the device substrate as a continuous resistor in a "herringbone" pattern or other design of

25   continuously connected multiple inclines, with the angle of incline being approximately 45° with respect to the direction of extension of the resistor. There then must be provided a source for a magnetic bias field which is oriented in a direction which is 90° to the direction of the

30   extension of the resistor.

Another method is to provide a linear strip of magnetoresistive material, with additional individual conductors across that strip at an angle of 45° with respect to the direction of the strip. This, in effect, causes the

5   current to flow at an angle through the magnetoresistive strip with respect to the direction of elongation of the strip itself. This latter configuration is often called a "barber pole" sensor because of its configuration, and such an arrangement can eliminate the need for an external

10   source of a magnetic bias field.

In magnetic recording heads the magnetization of the sensing layer of an AMR sensor is rotated by 45° in relation to the sense current by the stray field of an adjacent

15   magnetic layer magnetized perpendicular to the direction of the sensor strip. This layer can be a hard magnetic material (hard bias layer) or a soft magnetic material (soft adjacent layer) magnetized by the sense current.

20   In GMR or TMR elements the magnetization of the free layer has to be directed parallel to the strip direction. This is normally done by a hard bias layer placed on each side of the sensor. The magnetization of the pinned layers will be fixed perpendicular to the strip direction by

25   antiferromagnetic coupling.

Magnetostriction is an essential parameter for controlling the magnetic properties of thin films and multilayers. Magnetostriction describes the change in length of a

30   magnetic material by magnetic reversal.

In magnetic recording elements it is important to have homogeneously magnetized magnetic layers, especially the sensing layer (free layer) in the sensing layer stack. Inhomogeneously magnetized regions, like vortices or magnetic domains, cause instabilities in the recording signal. Therefore, the magnetic layers are aligned by local magnetic fields (exchange coupling field, hard bias field). Local inhomogeneities can be caused by magnetostrictive anisotropy. Therefore, the magnetostriction has to be controlled very precisely.

Various experimental methods have been developed for investigating the magnetoelastic properties of thin films. One of them is the direct measurement by the so-called "cantilever method". A change in magnetization leads to a change in length which with thin films causes bending of the substrate. This is, e.g., described in E. du Trémolet de Lacheisserie et al., "Magnetostriction and internal stresses in thin films: the cantilever method revisited", Journal of Magnetism and Magnetic Materials 136 (1994), pp. 189-196.

Another possibility is the indirect measurement by means of the strain gauge method, which creates mechanical stresses in a magnetic film. The magnetic anisotropy changes through magnetostrictive coupling. This is, e.g., described in D. Markham et al., "Magnetostrictive measurement of magnetostriction in Permalloy", IEEE Transactions on Magnetics, vol. 25, no. 5, September 1989, pp. 4198-4200.

An apparatus for measuring the magnetostriction constant of
a magnetic membrane is disclosed in Patent Abstracts of
Japan, JP 62106382 A2.

Kenji Narita et al., IEEE Transactions on Magnetics, vol.
Mag-16, no. 2, March 1980, pp. 435-439, disclose a method
to measure the saturation magnetostriction of a thin
amorphous ribbon by means of Small-Angle Magnetization
Rotation (SAMR).

However, no method is known to measure the magnetization
changes using the magnetoresistive effect of magnetic
sensors directly, so that the real environment of the
sensor is reflected. Therefore, there is still a need for
improvement of such methods.

Summary of the Invention

A system for directly measuring a magnetostriction value of
a magnetoresistive element, such as a magnetostriction
constant, includes a fixture for receiving a substrate
carrying one or more magnetoresistive elements. A magnet
assembly applies a first magnetic field, preferably a DC
field, parallel to the substrate. The magnet assembly also
applies a magnetic alternating field perpendicular to the
substrate and parallel to magnetoresistive layers of the
elements. A mechanism for applying a mechanical stress to
the substrate creates a stress oriented parallel to the
substrate. A measuring subsystem, which may be locked to
the frequency of the alternating field, measures a signal
from at least one of the magnetoresistive elements.

The system may further include a controller for changing
the first magnetic field, and a computing device for
calculating a magnetostriction constant of the at least one
magnetoresistive element based in part on e.g., a change of
mechanical stress anisotropy due to application of the
mechanical stress and the change in the first magnetic
field.

The substrate can be a row or a wafer, which may in turn
carry a plurality of the magnetoresistive elements such as
Anisotropic Magnetoresistance (AMR)-, Giant
Magnetoresistance (GMR)- or Tunneling Magnetoresistance
(TMR)-based sensors, and may further include shielding
layers, etc. The magnetoresistive elements may also be
magnetic memory elements.

The signal from the at least one of the magnetoresistive
elements is measured before the mechanical stress is
applied. After applying the mechanical stress, the first
5   magnetic field is changed until the signal being measured
co-currently thereto about matches the signal measured
before applying the mechanical stress.

The mechanism for applying the mechanical stress may cause
10   the substrate to bend. An illustrative mechanism is an
electronically or manually controlled micrometer screw.
Alternatively, the mechanism for applying the mechanical
stress may be a heat source, a heat sink, or a piezo layer.

15   Methods for directly measuring a magnetostriction value of
a magnetoresistive element are also disclosed.

Other aspects of the present invention will become apparent
from the following detailed description, which, when taken
20   in conjunction with the drawings, illustrate by way of
example the principles of the invention

Brief Description of the Drawings

FIG. 1 schematically depicts a system for measuring the magnetostriction constant according to a preferred method of the present invention.

FIG. 2 is a flow diagram of a process for measuring the magnetostriction constant according to one embodiment of the present invention.

Detailed Description of the Preferred Embodiment

In the present invention, the magnetostriction constant
(MS) in Anisotropic Magnetoresistance (AMR), Giant

5   Magnetoresistance (GMR) and/or Tunneling Magnetoresistance
(TMR) (in general XMR) based elements, like magnetic
recording heads, magnetic field sensors and the like, is
measured by small angle magnetization rotation (SAMR). The
electrical signal of the sensor is used to measure the

10 magnetization rotation caused by an external field. In
Magnetoresistance (MR) devices, the magnetization is biased
by various methods, e.g., hard bias, antiferromagnetic
exchange coupling, barber pole, etc. For the proposed M_S
measurement the bias fields (hard bias, soft bias, exchange

15 field) can be supported by an additional external DC field
(HDC) which is aligned parallel to the applied stress. If
the stress in the thin film is changed, the sensor signal
will also change due to magnetostrictive coupling. However,
the change of the sensor signal can be compensated by

20 changing the external DC field. For shielded elements the
external field is calibrated in order to reflect the
influence of demagnetizing effects from the shielding
layers. The stress can be applied on wafer or row level by
bending or by any other means like, e.g., temperature

25 change induced by heat source or heat sink, piezo layer,
etc.

The methodology according to the invention is not only
applicable to magnetic recording heads but can also be used

30 with other magnetic devices such as magnetic field sensors
and magnetic random access memories (MRAMs). However, for

the sake of simplicity, it is explained in the following
description with respect to magnetic recording heads.

FIG. 1 schematically depicts a system for measuring the
5   magnetostriction constant according to the methodology of
the present invention. As shown, a row or a wafer 10 is
inserted into a bending fixture, e.g., a deflection gauge
12, the row or wafer carrying XMR elements formed thereon.
Next, a first magnetic field, preferably a DC-field, is
10 applied parallel to the row or wafer 10, i.e., in the
direction of the x-axis shown in FIG. 1. A magnetic
alternating field is applied perpendicular to the row or
wafer 10 and parallel to the magnetoresistive layers, i.e.,
in the direction of the y-axis shown in the Figure. This
15 alternating field is preferably sinusoidal having the
frequency f. A measuring subsystem 14 measures a signal at
the magnetoresistive element, e.g., XMR element, this
signal being proportional to the amplitude of the
alternating field having the frequency f. To do this in a
20 simple way, a lock-in amplifier 14 can be used which is
locked to the frequency of the alternating field. A
mechanical stress is created in the layers of the XMR
element parallel to the x- direction by bending the row or
wafer 10, e.g., by means of a micrometer screw 16,
25 pneumatically or hydraulically actuated piston, solenoid,
etc. The screw or other stress-inducing mechanism can be
controlled electronically via line 20 by a control unit 48.
Due to the magnetoelastic interaction in the sensor layer
of the XMR element, the magnetic anisotropy will change.
30 This, in turn, will lead to a change in the amplitude of
the signal that is measured at the lock-in amplifier 14.

Finally, the applied magnetic DC-field in the direction of
the x-axis is changed by a suitable control circuit until
the measuring signal at the lock-in amplifier again reaches
the value that has been measured without having applied

5   mechanical stress. The magnet assembly 22 above the
row/wafer deflection fixture 12 is powered by an AC power
supply 42 for magnetic field generation in the y-direction,
and a DC power supply 24 for generating the DC compensation
field in the x-direction via lines 28 and 30. The XMR-

10   element is powered via line 32 by a constant current source
34. The sense output, the voltage across the XMR- resistor,
is fed via line 36 into the lock-in amplifier 14, being
locked to the excitation frequency of the magnetic AC field
via line 38, as already mentioned above. The whole

15   measurement assembly can be controlled by a computer 40 via
bus 26. Note also that the computer 40 itself can perform
some or all of the functions of, and/or replace, the
various components 34, 14, 42, 24, 48 in hardware,
software, or combinations thereof.

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FIG. 2 graphically illustrates a method 200 for directly
measuring the magnetostriction constant of a
magnetoresistive element according to preferred embodiment.
In operation 202, a substrate carrying one or more

25   magnetoresistive elements is provided. The substrate is
inserted into or onto a bending fixture in operation 204.
In operation 206, a magnetic DC field is applied parallel
to the substrate, while in operation 208, a magnetic
alternating field is applied perpendicular to the substrate

30   and parallel to the magnetoresistive layers of the
elements. A signal from the element is measured in

operation 210. A mechanical stress oriented parallel to the substrate is applied in operation 212 by bending the substrate. In operation 214, the magnetic DC field is changed until the current signal reading about matches the signal measured before applying the mechanical stress. In operation 216, the magnetostriction constant λ_s (or other value) is calculated. Illustrative formulae for calculating the magnetostriction constant and other values are presented below.

The magnetostriction λ_s is defined by the following formula

$$\frac{3}{2}\lambda_s * \Delta\sigma = \frac{1}{2}\Delta H_{k,\sigma} M_s \qquad\qquad (I)$$

that indicates that the magnetoelastic energy density (left side of the equation) is identical to the magnetic anisotropic energy density (right side of the equation).

The change of mechanical stress anisotropy $\Delta\sigma$ is connected with the strain change $\Delta\varepsilon = \frac{\Delta l}{l}$ (the relative elongation caused by bending of the row or wafer), by Hooke's law (being restricted to homogeneous and isotropic materials).

$$\Delta\sigma_x = \frac{E}{1-\nu^2}\left(\Delta\varepsilon_x - \nu\Delta\varepsilon_y\right), \Delta\sigma_y = \frac{E}{1-\nu^2}\left(\Delta\varepsilon_y - \nu\Delta\varepsilon_x\right)$$

The voltage change $\Delta\sigma$ is calculated from the mechanical parameters of the deflection:

$$\Delta\sigma = \Delta\sigma_x - \Delta\sigma_y = \frac{E}{1-\upsilon}\left(\Delta\varepsilon_x - \Delta\varepsilon_y\right) \tag{II}$$

The following methods can be used to obtain special
mechanical parameters:

1)   The strain can be calculated from the deflection (b in
     FIG. 1) by the following expression:

$$\Delta\varepsilon_x = \frac{3d_s * b}{2L^2}\left[1 - \frac{|x|}{L}\right], \tag{III}$$

where L is the bending length (cf. FIG. 1), d_s is the
substrate thickness (cf. FIG. 1), x = 0 at the center
of the strain gauge, and $\Delta\varepsilon_y = 0$.

2)   Measuring the surface curvature by scanning a laser
     beam over the sample surface. The laser is reflected
     from the row or wafer surfaces to a position sensitive
     optical device.

The strain $\Delta\varepsilon$ is determined from the deflection b or the
surface curvature in (II).

The measurement of the field of anisotropy follows from the
total energy:

$$E = H_x M_s \cos\vartheta - H_y M_s \sin\vartheta + \frac{1}{2}H_k M_s \sin^2\vartheta + \frac{1}{2}\left\langle N_{demag}\right\rangle M_s^2 \sin^2\vartheta \tag{IV}$$

This term includes the energy in the external fields (H_x, H_y), the uniaxial anisotropy (H_k), which is composed of the induced anisotropy and the magnetostrictive anisotropy, as well as the form anisotropy, which takes into account the distribution of the magnetization of the layer to be measured.

From the condition of equilibrium dE/d = 0 follows:

$$\sin\vartheta = \frac{H_y}{H_x + H_k + \langle N_{demag}\rangle M_s} \qquad (V).$$

Given a periodic excitation field $H_y = H_{yo}\sin(\Phi t)$, the magnetization will fluctuate around a state of equilibrium. The resistance of a magnetoresistive element changes with the identical frequency.

A mechanical tension changes the anisotropic field H_k. This, in turn, causes a change in resistance and a change in amplitude of the fluctuations of the magnetization. These changes are compensated by means of the external field H_x and the original state of equilibrium is restored. The following equation applies:

$$\Delta H_{k,\sigma} = \Delta H_x \qquad (VI).$$

The calculation of λ_s is straight forward. The strain $\Delta\varepsilon$ can be calculated, e.g., from (III). The stress anisotropy $\Delta\sigma$ is then derived from (II). From (I) the magnetostriction

constant can be calculated by inserting $\Delta\sigma$, and $\Delta H_{k,\sigma}$ from (IV).

The saturation magnetization M_s and the elasticity constants E and v are inserted into equation (I) as constants.

One skilled in the art will appreciate that calculations using the foregoing equations can be performed in hardware or software, such as by the computer 40 in FIG. 1. The calculation details and results can then be stored or transmitted in electronic form, tabulated for multiple elements on the substrate and/or for elements across various substrates, displayed in visual form, output on paper, etc.

Also, as an alternative, the first magnetic field can be a static field from a hard magnet. To vary the field, the distance between the magnet and the substrate can be varied.

The present invention suggests using the MR-effect of the magnetic sensors directly for the measurement of the magnetization changes. The methodology according to the present invention has the following advantages, among others:

- The use of a compensation method guarantees a fixed magnetization state, which avoids errors by local magnetization distributions in structured films. Bias fields, e.g., softbias in anisotropic magnetoresistive

sensor (AMR), longitudinal magnetically hard fields (hardbias) or exchange fields adjacent magnetic layers do not have any effect.

- The measurement is simple and fast.
- The MR effect is very sensitive.
- The measurement can be performed in the sensor elements themselves. There is no need to have separately-manufactured monitor layers.

While various embodiments have been described above, it should be understood that they have been presented by way of example only, and not limitation. Thus, the breadth and scope of a preferred embodiment should not be limited by any of the above-described exemplary embodiments, but should be defined only in accordance with the following claims and their equivalents.